

# Beam clean-up and combining via stimulated scattering in liquid crystals

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**Abstract:** Orientational stimulated scattering from o-wave into e-wave in liquid crystal may combine coherent beams or modes of amplifier(s) into diffraction-limited output. In experiment a 1000 micron liquid crystal layer transmitted undistorted o-wave with low attenuation.

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**OCIS codes:** (140.3300) Laser beam shaping, (160.3710) Liquid crystals, (190.5890) Scattering, stimulated

## 1. Introduction

Modern diode-pumped fiber lasers and solid-state lasers can work in the regime of Power Amplifiers (PA) and thus provide output power in the scale of Kilowatt and more. Crucial problem exists of making a beam of diffraction quality out of resultant radiation. Combining the outputs of several fiber lasers, when each of them is fed by the same signal from Master Oscillator (MO), and each works on a single transverse mode, may be done by multibeam analogs of Mach-Zender interferometer. The phase of each of the beams there is to be controlled electro-optically. However, clean-up of a beam with distorted (albeit coherent) transverse structure, as well as combining several such beams can not be done directly by the interferometric schemes.

We suggest here the device to clean-up and combine transversely and mutually coherent beams of possibly distorted transverse structure into one diffraction-quality beam. The process in question is Stimulated Orientational Scattering from e-wave into o-wave in a cell with Nematic Liquid Crystal (NLC).

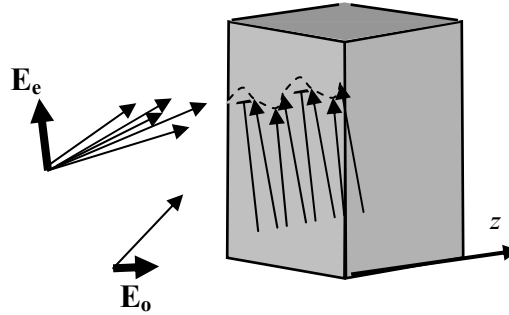


Fig. 1. Interference of distorted pump wave ( $E_e$  in our case) with the diffraction-quality signal beam ( $E_o$  in our case) results in the change of orientation of NLC's director. Scattering of pump into signal by this grating yields energy transfer with the preservation of beam quality.

## 2. Theoretical estimations

Energy exchange via Stimulated Scattering of light is characterized by gain coefficient

$$g[1/m, \text{intensity}] = G \cdot S_{e,o}, \quad (1)$$

where  $S$  is Poynting vector of the wave. Stimulated Scattering by orientation gratings in NLC has this value of gain constant  $G$ , see [1, 2]:

$$G = \frac{\pi}{\lambda_{\text{vac}}} \left( n_e^2 - n_o^2 \right)^2 \frac{1}{K_{22} q^2 c n_e n_o} \equiv \frac{\lambda_{\text{vac}}}{\pi} \left( \frac{n_e + n_o}{2} \right)^2 \frac{1}{K_{22} n_o n_e c} \quad (2)$$

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Here  $S_{e,0} = 0.5cn_{e,0}\epsilon_0|E_{e,0s}|^2$  are the values of the Poynting vector of the corresponding waves (Watt/m<sup>2</sup>), and the coefficient  $G$  (m/Watt) gives the intensity gain  $g$  of the signal at the optimal frequency shift  $\Gamma = +\Omega$ , so that  $S_0(z) = S_0(0)\exp(gz)$  in the approximation of the undepleted pump, which is e-wave in our case. . The value of  $G$  is

$$G = \frac{\pi}{\lambda_{\text{vac}}} (n_e^2 - n_o^2)^2 \frac{1}{K_{22}q^2 cn_e n_o} \equiv \frac{\lambda_{\text{vac}}}{\pi} \left( \frac{n_e + n_o}{2} \right)^2 \frac{1}{K_{22}n_o n_e c}. \quad (2)$$

This kind of steady state stimulated scattering in a planar NLC cell has been observed in [3, 4] in complete agreement with theory.

Taking  $\lambda_{\text{vac}} = 1 \mu\text{m}$ , elastic constant of NLC  $K_{22} = 4 \cdot 10^{-12}$  Joule/m, refractive index  $n \approx 1.5$ , one gets  $G = 6 \cdot 10^{-4}$  m/Watt  $\equiv 0.06$  cm/Watt. It means that the undepleted amplification factor for the intensity of the signal at the thickness of the cell  $L = 500 \mu\text{m}$  and for the pump Poynting vector  $S_p = 3 \cdot 10^3$  Watt/cm<sup>2</sup> is  $\exp(GS_p L) = e^9 = 0.8 \cdot 10^4$ . We have all the reasons to assume that such an amplification factor will be quite sufficient for almost complete energy transfer from the multi-transverse-mode pump into the clean signal beam.

The relaxation time  $\tau = 1/\Gamma$  depends on the value of the optical anisotropy and on the orientational viscosity of the NLC that is chosen. Taking, for example,  $n_e - n_o = 0.2$  and  $\eta = 0.1$  Pa-sec, one gets  $\Gamma = K_{22}(n_e - n_o)^2 (2\pi/\lambda_{\text{vac}})^2/\eta = 63$  rad/s,  $\Omega_{\text{opt}}/2\pi = \Gamma/2\pi = 10$  Hz,  $\tau = 1/\Gamma = 16$  millisecond. That requires that the phase shift between various pump beams or modes should not drift more than 1 radian during 20 millisecond or so. Determining whether this is possible requires physical experiments with the particular laser set-up.

### 3. Preliminary experimental set-up

We have prepared a cell with Nematic Liquid Crystal of planar orientation. Special configuration of the cell: the thickness changed from 100 micron to 1000 micron at the distance about 48 mm, resulting in a birefringent wedge (mini-prism), which allows to study energy transfer and propagation properties at different values of interaction thickness  $L$ . Fig. 2 shows propagation of o-wave (left picture) and e-wave (right picture) through 750 microns of NLC in the region with rather strong distortions. One sees that o-wave remains practically un-distorted, in agreement with earlier predictions [5] and experiments [6]. Sure, there were regions of the cell with smaller distortions even for e-wave.

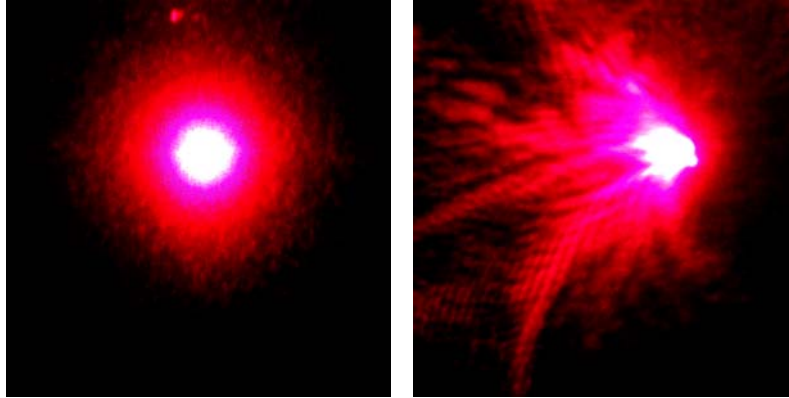


Fig. 2. Un-distorted transmission of ordinary wave (left) and rather strong distortions in the transmission of extraordinary wave (right) through “bad spot” with the thickness 750 microns of planar NLC cell.

We made preliminary measurements of extinction coefficient by this NLC at  $\lambda = 632$  nm. Since we can not distinguish between actual absorption, extinction due to scattering, and other loss, our estimation is  $R_e \leq 9$  [1/cm] and  $R_o \leq 8$  [1/cm] respectively. Scattering in LNC scales approximately as  $1/\lambda^2$ , and therefore we can expect about 4 times smaller scattering at  $\lambda = 1.06$  micron. In the talk we will present the results of the study of beam clean-up.

To conclude, the possibility of beam clean-up via stimulated scattering in Liquid Crystals seems realistic.

## References

1. B. Ya. Zeldovich, A. V. Sukhov, N. V. Tabirian, *The Orientational Optical Nonlinearity of Liquid Crystals*, Special issue of Mol. Cryst. & Liq. Cryst. **136**, #1, 140 pages, 1986.
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3. I. I. Goosev, et al., Sov. Phys. JETP Lett., **55**, 178-183 (1992).
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CLEO'2003, Baltimore, June 04.

# Overview of the talk

1. High-power CW solid-state and fiber lasers are here !
2. Combining several beams and beam clean-up are important problems.
3. Idea: to combine several mutually coherent beams or angular components via Stimulated Scattering.
4. Particular design: Liquid Crystal with o-type signal wave and e-type pump wave.
5. Estimations of the required power and heat transfer.
6. Experimental set-up.
7. Demonstration of Orientational Stimulated Scattering
8. Conclusion.

# **High-power CW solid-state and fiber lasers are here !**

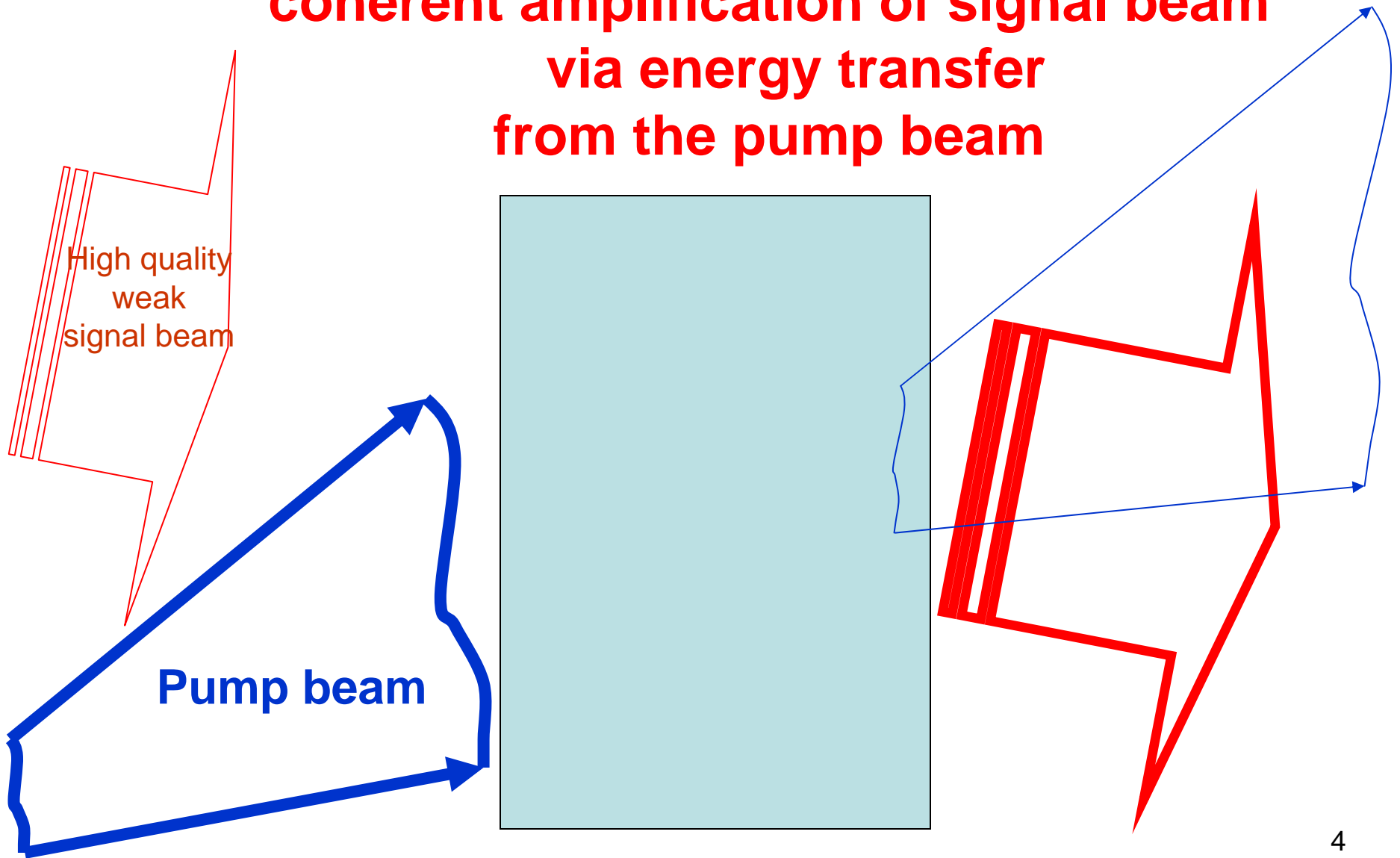
**They have the power more than 1000 Watt now  
and promise much more.**

**Beam clean-up and combining the energy from  
several amplifiers look attractive.**

**However, Louiville's (Lagrange-Helmholtz) theorem  
does not permit to increase brightness  
by linear-optical devices.**

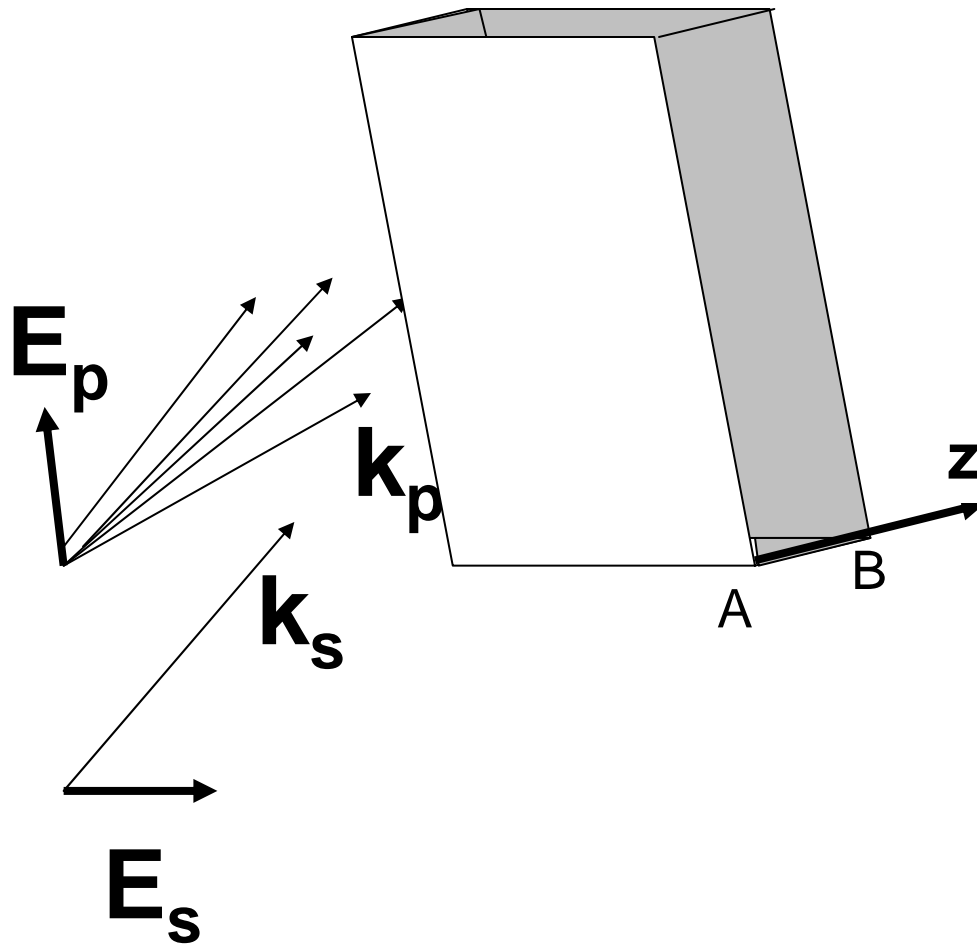
# Stimulated Scattering:

coherent amplification of signal beam  
via energy transfer  
from the pump beam



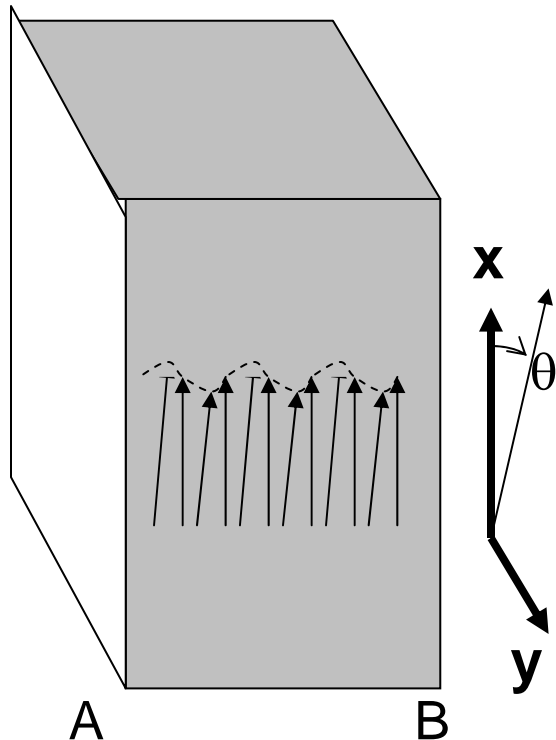


**Suggested in this work:  
to use orientational Stimulated  
Scattering in a Nematic Liquid Crystal**



Signal plane wave  $\mathbf{E}_s$  and inhomogeneous pump wave  $\mathbf{E}_p$  have slightly different frequencies,  $\omega_p - \omega_s = \Omega$ . They illuminate liquid crystal cell with a planar orientation of the director.

# Grating-type Orientational Nonlinearity (GRON) in a Nematic Liquid Crystal



Interference of  $\mathbf{E}_s$  and  $\mathbf{E}_p$  yields the grating with director orientation  $\delta\mathbf{d} \propto \exp[i\Omega t - i(\mathbf{k}_p - \mathbf{k}_s) \cdot \mathbf{r}]$ . Scattering of the pump  $\mathbf{E}_p$  by this grating of dielectric permittivity results in amplification of the signal  $\mathbf{E}_s$ .

References on stimulated scattering in LC:

- N. V. Tabirian, A. V. Sukhov, B. Ya. Zeldovich, M.C.L.C. **136**, #1, pp. 1-140, 1986.
- I. I. Goosev et al., JETP Lett., **55**, p. 178, 1992.
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- N. V. Tabirian, A. V. Sukhov, B. Ya. Zeldovich, JOSA **B**, **18**, pp. 1203-06, 2001  
(well-saturated regime at pump level about 0.5 Watt for  $\lambda = 1.06 \mu\text{m}$ )

## System of basic equations in steady-state approximation

$$\frac{\partial E_s}{\partial z} = E_s \frac{G[(\Omega/\Gamma) - i]}{[1 + (\Omega/\Gamma)^2]} S_p, \quad \frac{\partial E_p}{\partial z} = -E_p \frac{G[(\Omega/\Gamma) - i]}{[1 + (\Omega/\Gamma)^2]} S_s$$

$$G = \frac{\pi}{\lambda_{\text{vac}}} (n_e^2 - n_o^2)^2 \frac{1}{K_{22} q^2 c n_e n_o} \equiv \frac{\lambda_{\text{vac}}}{\pi} \left( \frac{n_e + n_o}{2} \right)^2 \frac{1}{K_{22} n_o n_e c}$$

Here  $E_p$  is pump field,  $E_s$  is signal field,

$S_p$ ,  $S_s$  are the corresponding values

of Poynting vector,  $G$  is the gain constant  
at the “optimum” frequency shift  $\Omega = \Gamma$ .

## Estimations

For NLC with  $n_e - n_o = 0.2$ ,  $\lambda_{vac} = 1 \mu m$ ,  
 $K_{22} = 4 \cdot 10^{-11}$  Newton ( $4 \cdot 10^{-6}$  dyne),  $n \approx 1.5$ ,  
one gets  $G = 6 \cdot 10^{-5}$  m/Watt.

Taking cell thickness  $L = 0.5$  mm,  
pump Poynting vector

$$S_p = 30 \text{ KWatt/cm}^2 \equiv 3 \cdot 10^8 \text{ Watt/m}^2,$$

one gets signal amplification

$$\exp(G S_p L) = e^9 \approx 10^4.$$

# Estimations of thermal load

If we take an estimation of the true absorption coefficient,  $\alpha \approx 0.01 \text{ m}^{-1} \equiv 0.0001 \text{ cm}^{-1}$ , then the fraction of the light absorbed in the  $L=500$ -micron layer is about  $f=\alpha L \approx 5 \cdot 10^{-5}$ . At the value of the incident Poynting vector  $S$  of about  $30 \text{ KWatt/cm}^2$ , such an absorption yields a thermal power deposition  $Sf \approx 0.15 \text{ Watt/cm}^2$  of the beam area.

Taking the order of magnitude of thermal conductivity coefficient for NLC  $\Lambda \approx 1.3 \cdot 10^{-3} \text{ Watt/cm} \cdot \text{K}$ , and a cell thickness  $L = 500$  micron, we get from the steady-state solution of the thermal conductivity equation:

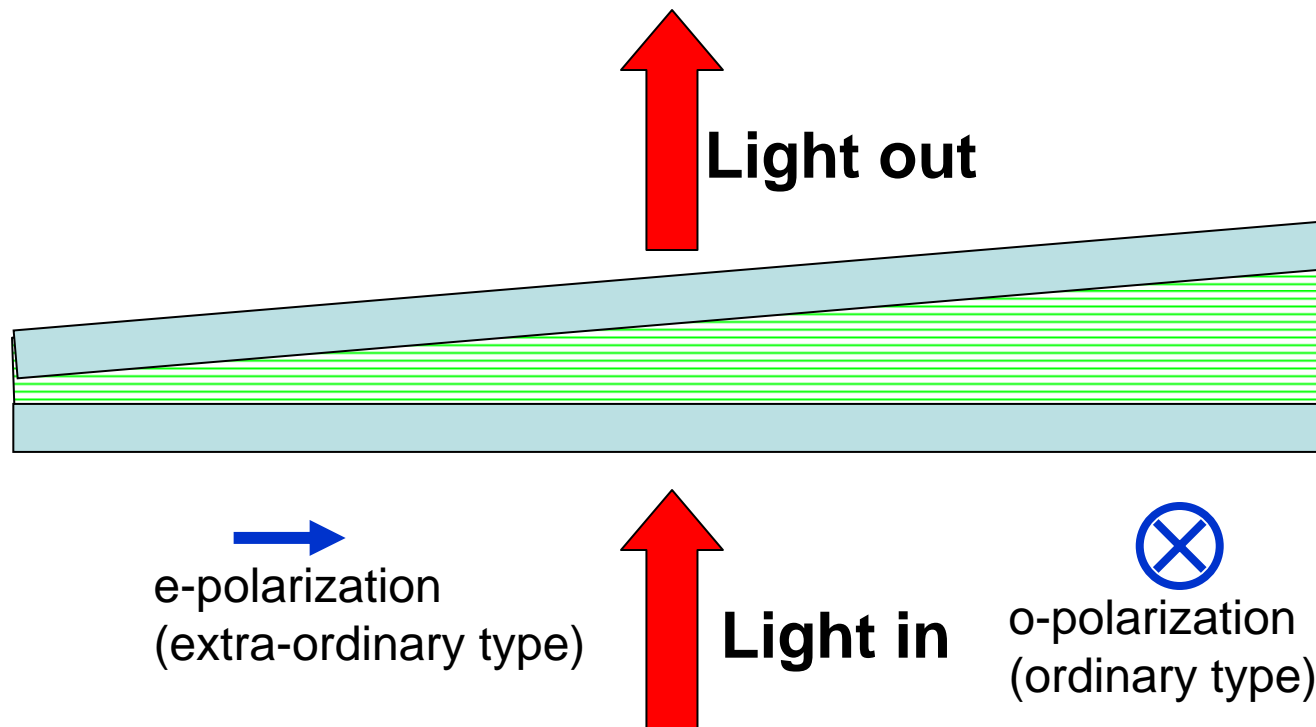
$$\delta T_{\text{center}} = fSL/8\Lambda \approx 0.7 \text{ K}.$$

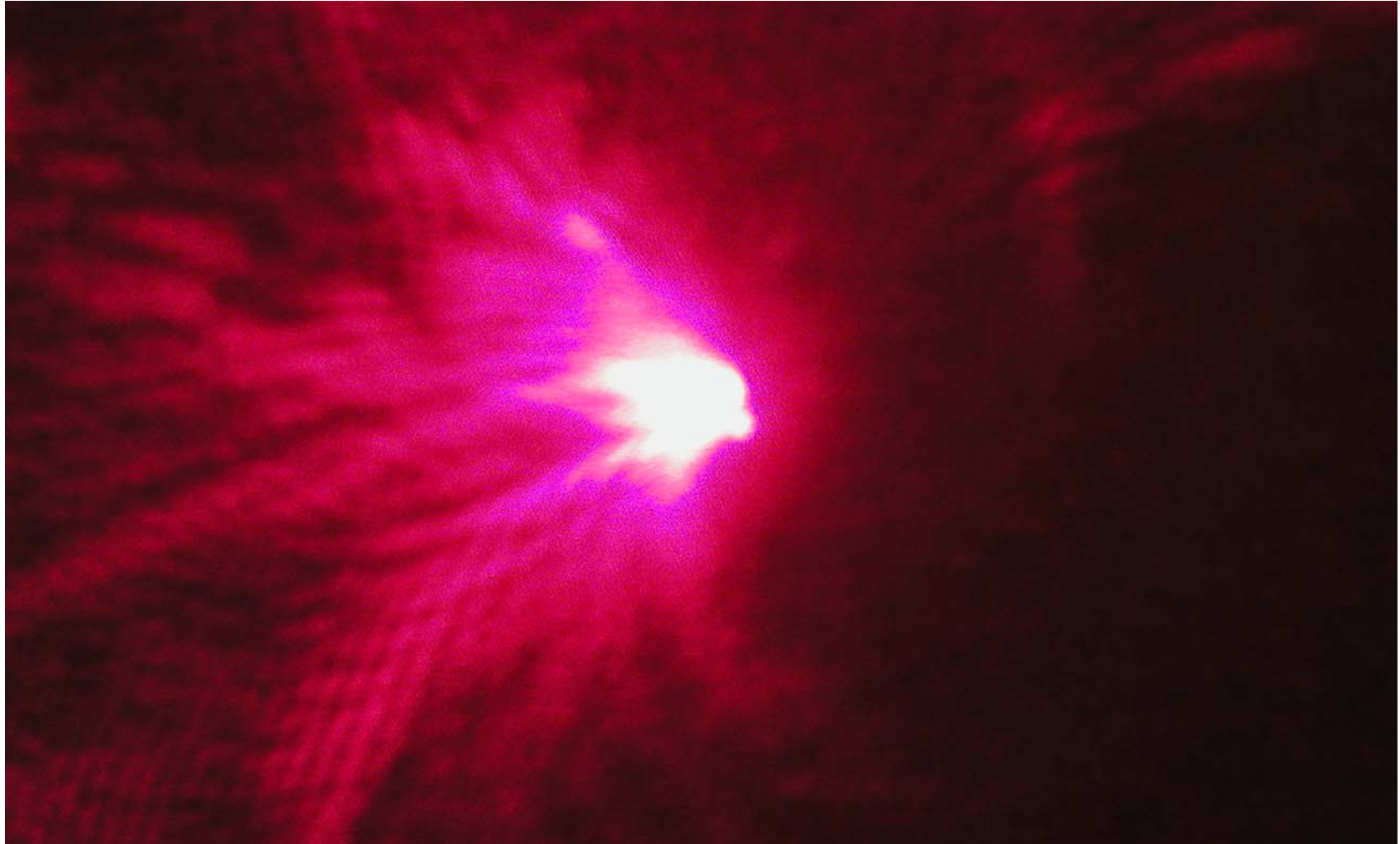
The flux of thermal power through one of the two sapphire walls,  $0.5fS \approx 0.075 \text{ Watt/cm}^2$ , can be maintained with a temperature gradient of  $0.5fS/\Lambda_{\text{sapphire}} = 0.2 \text{ K/cm}$ .

# Experiment

We used LC cell with Nematic Liquid Crystal of planar orientation.

To try various values of thickness of the cell, we used a wedge-type cell, with the thickness varying from 100 to 1000 micron at 5 cm of length.





**Extraordinary wave,  $\lambda = 632.8$  nm,  
transmitted through 800 micron of planar NLC cell.  
Distortions are rather strong.**



**Ordinary wave,  $\lambda = 632.8$  nm,  
transmitted through 800 micron of planar NLC cell.  
Distortions are practically absent.**



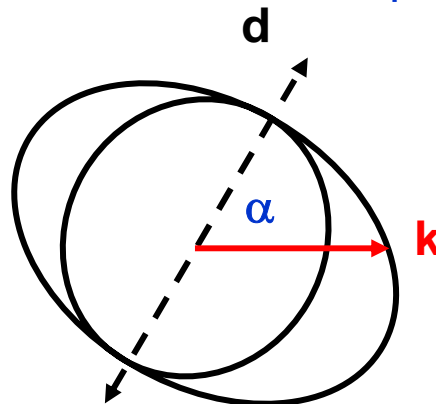
# Reasons for distortion-less transmission of the ordinary-type wave

(N. B. Baranova, I. V. Goosev, V. A. Krivoschekov, B. Ya. Zeldovich,  
Molecular Crystals & Liquid Crystals J., 210, 155, 1992,

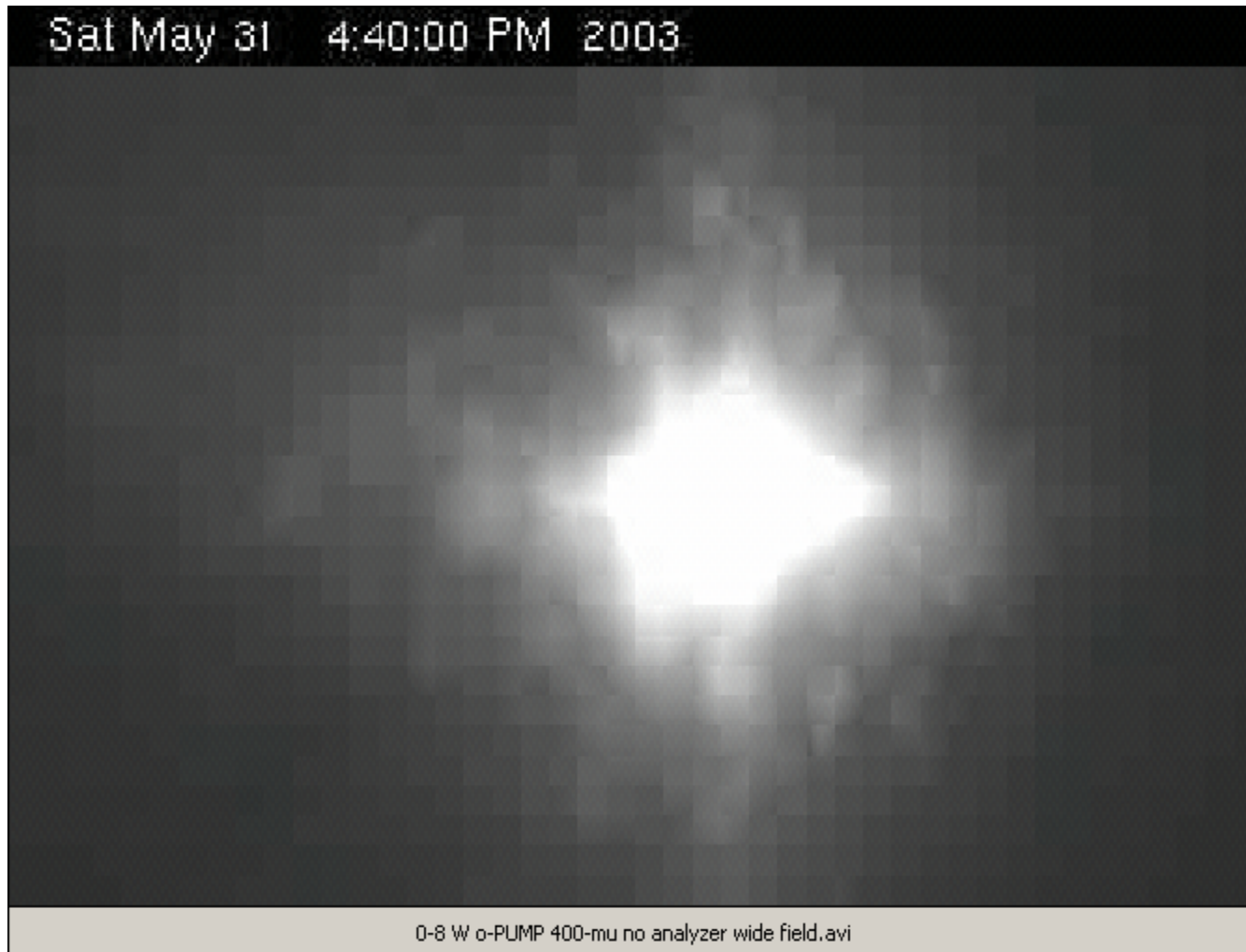
*Distortionless Propagation of O-wave through Inhomogeneous Nematic (Theory and Experiment.)*

1. Polarizations of both ordinary and extra-ordinary waves follow adiabatically the local orientation of director.
2. Input and output o- and e-polarizations are prescribed by the boundaries and thus are preserved.
3. Phase velocity of the e-wave varies with the variations of the angle  $\alpha$  between propagation **k**-vector and director **d** (ellipsoid ! ).
4. Phase velocity of the o-wave is constant at any angle  $\alpha$  (sphere ! ).

Therefore o-wave does not acquire  
ether phase distortions or polarization distortions.



# Observation of Stimulated Grating Orientational Scattering in NLC



$\lambda = 1.08 \text{ mkm}$ ,  
Yb-doped IPG  
fiber laser,  
output power  
100 W, power to  
the cell 0.8 W.  
Lens  $F = 20 \text{ cm}$ ,  
beam  $\varnothing = 5 \text{ mm}$   
(FWe<sup>-2</sup>M)  
at the lens.

# Observation of Stimulated Grating Orientational Scattering in NLC



$\lambda = 1.08 \text{ mkm}$ ,  
Yb-doped IPG  
fiber laser, output  
power 100 W,  
power to the  
cell 3.2 W.  
Lens  $F = 20 \text{ cm}$ ,  
beam  $\varnothing = 5 \text{ mm}$   
(FWe<sup>-2</sup>M)  
at the lens.  
Cell was  
out of focus.

# Observation of Stimulated Grating Orientational Scattering in NLC



Power to the  
cell 1.6 W.  
Lens  $F = 20$  cm,  
beam  $\varnothing = 5$  mm  
(FWe<sup>-2</sup>M)  
at the lens.  
Cell was in focus.  
Analyzer transmitted  
mostly the scattered  
wave. Almost no  
o-wave pump is left.

## Potential problems to be overcome. 1.

$$\frac{\partial E_s}{\partial z} = E_s \frac{G[(\Omega/\Gamma) - i]}{[1 + (\Omega/\Gamma)^2]} S_p$$

Term  $(-i)$  means Cross-Phase Modulation (CPM)  
at the “optimum” frequency shift  $\Omega = \Gamma$ .

It may distort the phase of the cleaned signal beam.

Some of the ways to overcome CPM's influence.

Make the profile of pump's Poynting vector  
approximately parabolic.

Take “super-optimum” frequency shift, e.g.  
 $\Omega = 3\Gamma$ . Then gain will be damped by factor 0.6,  
while CPM will be damped by factor 0.1.

Use double-phase conjugation scheme.

## Potential problems to be overcome. 2.

Time coherence is required between the signal and the beam(s) to be combined and/or cleaned-up.

What to do about it ?

Coherence is not an issue, if the spectrum of our MO-PA device is narrow enough.

Equal optical paths for various channels, angular components etc. should be provided within the coherence length.

## Conclusions

1. Stimulated Scattering in Nematic LC is suggested for the beam combining and clean-up.
2. Inhomogeneities of NLC orientation do not distort ordinary wave, even at  $L = 1$  mm.
3. Stimulated scattering at  $1.06\text{ }\mu\text{m}$  is demonstrated in the work by Tabirian, Sukhov & Zeldovich, and at  $1.08\text{ }\mu\text{m}$  here.
4. NLC cell and LC material within it are shown to tolerate at least  $100\text{ KWatt / cm}^2$  of CW light.
5. Perspectives of beam combining and clean-up for high-average power beams look promising.